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OPTICAL PROPERTIES OF PARTICULATE MATTER EMITTED BY FIRES (PILOT STUDY)

Optical Properties of Particulate Matter Emitted by Fires (Pilot Study)

Final Report for the

JOINT VENTURE AGREEMENT 03-JV-11222049-102
BETWEEN THE
USDA FOREST SERVICE
ROCKY MOUNTAIN RESEARCH STATION
RESEARCH WORK UNIT NUMBER 4404
AND THE
DESERT RESEARCH INSTITUTE

Prepared by

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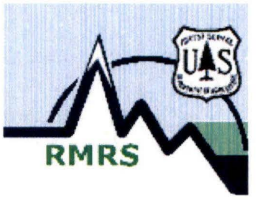

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INTRODUCTION

The purpose of this study was to characterize the optical properties (i.e., light absorption, scattering, and extinction) of particulate matter emitted by forest fires with the ultimate goal to a) understand their influence on visibility degradation and radiative transfer in the atmosphere, and b) to be able to better analyze data obtained with optical remote sensing (e.g., Lidar and satellite spectrometers) for the characterization of smoke plumes.

The centerpiece of this study was a two-week joint measurement period that took place during November 2003 in the Combustion Laboratory of the Missoula Fire Science Laboratory (FSL). This measurement program was a joint effort of The USFS FSL, our group at the DRI (Desert Research Institute) and a group from CSU (Colorado State University).

Preparations included the following tasks: 1) development of a matrix of fuels and combustion conditions, 2) deciding on instrumentation to be deployed, 3) development of an aerosol sampling scheme for all instruments, and 4) preparing and adapting the DRI instrumentation for the joint measurement period. Tasks 1-3 were accomplished in close cooperation with participating FSL and CSU scientists. After extensive preparation, a planning meeting including DRI, CSU, and FSL scientists took place at the end of May 2003 in Missoula, Mt at the FSL. Most major decisions regarding the planned measurements were made during this meeting, followed by some fine-tuning.

The main measurement period took place from November 10, 2003 through November 22, 2003. During this period 75 burns of mostly forest fuels were conducted and characterized. The CSU group did not participate in some of the initial burns, but conducted additional burns after the 75 burns discussed here.

During the following year, data from these experiments were compiled, analyzed, and quality assured. These data include new results on the optical, physical, and chemical composition of particles emitted from the combustion of wildland fuels as function of fuel and combustion conditions. Preliminary results were presented in three conference presentations, some example data were used in one peer-reviewed publication, and several publications are still in preparation for submission to peer-reviewed journals. This final report summarizes information on the burns and on the DRI measurements.

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FACILITIES AND INSTRUMENTATION

The combustion facility at FSL measures 12.5 m by 12.5 m by 22 m high (Figure 1) (Christian et al., 2003). A 1.6-m diameter exhaust stack with a 3.6 m inverted funnel opening extends from 2 m above the floor through the ceiling. The room is pressurized with outside air that has been conditioned for temperature and humidity, and is then vented through the stack, completely entraining the emissions from fires burning beneath the funnel. The fires are burned on a continuously weighed fuel bed. A sampling platform surrounds the stack at 17 m elevation where all the temperature, pressure, gas and particle measurement equipment for this experiment was deployed. Sampling pumps were deployed on the ground floor with long, flexible pipes connecting them to the equipment on the measurement platform. Additional equipment on the ground floor included cameras for continuous visible and infrared imagery of the combustion process (FSL group).

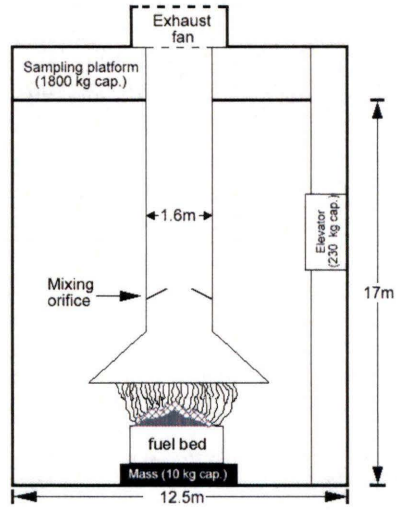

Fig. 1: Schematic diagram of the FSL combustion facility (Christian et al., 2003).

Instruments and emission sampling equipment deployed by DRI include:

1. **Photoacoustic Instruments (PA)** for the measurement of aerosol optical absorption coefficients at 532 nm and at 1047 nm. Electromagnetic energy absorbed by aerosol is converted to heat. Because the aerosol particles are small, and have sufficiently high thermal conductivity, the absorbed heat will flow rapidly to the surrounding air. Heated air responds by expanding its volume and/or pressure. By placing the aerosol-laden air into an acoustic resonator, and modulating the electromagnetic power at its resonance frequency, the varying pressure disturbance (acoustic signal) can be amplified by the buildup of a standing acoustic wave in the resonator. Thus by measuring the sound pressure that is associated with aerosol light absorption, the light absorption coefficient can be obtained. Our photoacoustic instrument (Arnott et al., 1999), its calibration (Arnott et al., 2000), some theory involved (Raspet et al., 2003), and some results from photoacoustic measurements (Moosmüller et al., 1998; Moosmüller et al., 2001a; Moosmüller et al., 2001b; Arnott et al., 2003; Arnott et al., 2005) have been described with more details in multiple publications.
2. **Integrating Sphere Integrating Nephelometer (ISIN)** for the measurement of aerosol optical scattering coefficients at 532 nm. The ISIN is a novel and unique reciprocal nephelometer that uses an integrating sphere with attached truncation-reduction tubes to contain the sample volume and to integrate the scattered light. Its main advantage over current integrating nephelometers is the seven-fold reduction in truncation angle, which reduces errors in measured scattering from large particles. Additional features include the improved sampling efficiency for large particles and the well-defined operating wavelength. The ISIN (Varma et al., 2003), the theory behind truncation errors (Moosmüller and Arnott, 2003), and one initial application (Moosmüller et al., 2005b) have been described previously.

3. **Cavity Ring-Down (CRD) and Cavity-Enhanced Detection (CED) Instrument** for the measurement of aerosol optical extinction coefficients at 532 nm. CRD measures the lifetime of photons in a high-quality optical cavity and thereby determines the sum of sample extinction between the cavity mirrors and that due to mirror losses. CRD systems can be calibrated with a single gas for the determination of extinction. A green laser emitting sub-nanosecond pulses is used as a light source facilitating measurements free from optical interference in the cavity. The addition of a low-frequency chopper allows for the determination of extinction coefficients with simple linear fitting procedures and also facilitates CED measurements by providing laser power modulation for phase-sensitive detection. CED measures the average power transmitted by the optical cavity. After calibration with two gases, CED allows for the independent measurement of extinction with very high dynamic range and for an independent comparison with CRD measurements, thereby increasing confidence in the measurements. This instrument combining CRD and CED measurements has been described previously (Moosmüller et al., 2005a).

4. **Tapered Element Oscillating Microbalance (TEOM)** for the real time aerosol mass measurement. A continuous measurement of the inertial mass of aerosol deposited on a filter substrate has been implemented using tapered element oscillating microbalance technology (Patashnick and Hemenway, 1969; Patashnick and Rupprecht, 1991). This technology utilizes a hollow tube, with the wide end of the tapered tube fixed. The narrow end of the tube holds a filter cartridge, and a sample is passed through the filter and tube to a flow controller. The tube-filter unit acts as a simple harmonic oscillator with its oscillating frequency being a function of filter mass loading. The system can be calibrated by placing a calibration mass on the filter and recording the frequency change due to this mass (Horodecki and Fißan, 1996). As the oscillating frequency is a function of temperature, the tapered tube, filter, and sampled air are temperature stabilized, typically at 50 °C. The heating prevents condensation and provides a standard sample conditioning in respect to the removal of semi-volatile components. However, this aerosol conditioning is different from filter sampling techniques and may remove more volatile compounds due to heating (Shore and Cuthbertson, 1985; Allen et al., 1997; Allen, 1998a; Allen, 1998b; Okrent, 1998; Patashnick, 1998a; Patashnick, 1998b; Rogers et al., 1998). A commercially available TEOM designed for the real time measurement of diesel particulate mass (Rupprecht & Patashnick Co., Inc. TEOM Series 1105) has been used in this study (Shore and Cuthbertson, 1985; Whitby et al., 1985; Patashnick, 1987; Okrent, 1998).

5. **Aerosol Sampling on Teflon Filters for Gravimetric Analysis and Optical Densitometry.** Teflon filters are weighed before and after sampling in the DRI Environmental Analysis Facility. During sampling, the sample is drawn through the filter at a controlled flow rate with a well-defined sampling period. This makes it possible to convert the aerosol mass deposited on the filter to an aerosol mass density in the sample. The weighing is done with a Mettler Toledo MT5 Microbalance to the nearest 0.001 milligram. Humidity changes affect the mass of filters and their deposits by changing the amount of absorbed water on the sample. To minimize this effect, filters are equilibrated and weighed in a temperature and humidity controlled environment (20 to 23 °C and 30% to 40% RH acceptable, 21.5 ± 2 °C and 35% ± 5% RH preferred). Light attenuation through the Teflon filters is measured before and after sampling with a Tobias TBX-10 Densitometer. This instrument operates with "white" light, however, the effective spectral weighting (i.e., convolution of source and detector spectrum)

is not known to us. Light attenuation due to aerosol particles accumulated on these filters is reported as an absorption coefficient with dimension of inverse distance without any calibration factor to compensate for deficiencies of the integrating plate method (Moosmüller et al., 1998).

6. **Aerosol Sampling on Quartz-Fiber Filters for Thermal Optical Analysis of Organic/Elemental Carbon.** EC (elemental carbon) and OC (organic carbon) can be distinguished with the help of the refractory properties of EC using thermal/optical filter analysis methods, where the optical component monitors and compensates for the pyrolysis (charring) of OC. A commonly used method is the Thermal/Optical Reflectance (TOR) carbon analyzer developed by Huntzicker et al. (Huntzicker et al., 1982). Our work uses a variation of this method using both TOR and TOT (Thermal/Optical Transmittance) to monitor and correct for pyrolysis (Chow et al., 1993; Chow et al., 2001). While all thermal/optical instruments operate similarly, EC and OC are operationally defined and the specific instrument used, the use of TOR or TOT for the pyrolisis correction, and details of its operation influence the split between EC and OC (Chen et al., 2004; Chow et al., 2004).

7. **Aerosol Sampling on Nuclepore Filters for Scanning Electron Microscopy (SEM) Analysis.** SEM imagery was used to investigate the morphology of particle emitted from the burns. Particles were sampled on Nuclepore clear polycarbonate 13-mm diameter filters mounted in Costar Pop-Top Membrane holders. The filters were analyzed using a Hitachi Scanning Electron Microscope (SEM) Model S-4700 at the Metallurgical and Materials Engineering Division (Dr. M. Misra) of the University of Nevada, Reno. This analysis yielded images of the particles for the determination of shape, size, and fractal dimensions. In addition, x-ray fluorescence analysis was performed on individual particles. Due to the interference with the polycarbonate filter substrate, this analysis did not yield quantitative information about the carbon-oxygen ratio of the particles. However, some information was gained as some particles contained significant quantities of potassium chloride of silicon.

8. **Aerosol Sampling on Teflon-Impregnated Glass Fiber (TIGF) Filters Backed with PUF-XAD Cartridges for Organic Analysis.** Samples were collected by drawing 113 LPM through Teflon impregnated glass fiber (TIGF) filters with polyurethane (PUF) and polymeric resin XAD-4 sandwich cartridges placed behind for collection of semi-volatile compounds. These samples were analyzed at the DRI Organic Laboratory (Director: Dr. Barbara Zielinska). Several isotopically labeled internal standards were added to each TIGF filter and PUF/XAD-4/PUF cartridge sample prior to extraction. The internal standards added included: hexanoic-d11 acid, benzoic-d5 acid, succinic-d4 acid, decanoic-d19 acid, adipic-d10 acid, suberic-d12 acid, levoglucosan-u-13C6, homovanillic-2,2-d2 acid, myristic-d27 acid, heptadecanoic-d33 acid, oleic-9,10-d2 acid, tetradecanedioic-d24 acid, cholesterol-2,2,3,4,4,6-d6. The TIGF filter was extracted separately from the PUF/XAD-4/PUF cartridge to evaluate the semi-volatile nature of these compounds. Samples were extracted using the Dionex Assisted Solvent Extraction (ASE) apparatus with dichloromethane followed by acetone. These extracts were then combined and concentrated by rotary evaporation followed by moisture filtered ultra high purity (UHP) nitrogen blow down and then split into two fractions. The first fraction was archived. The second fraction was evaporated to 100 µl under moisture filtered UHP nitrogen and transferred to 300µl silanized glass inserts (National Scientific Company, Inc.). Samples were further evaporated to 50µl, and 25µl of pyridine, 25µl of the internal standards, and 150µl of BSTFA with 1% TMCS

(N, O-bis (trimethylsilyl) trifluoroacetamide with 1% trimethylchlorosilane (Pierce)) were added. These derivatizing reagents convert the polar compounds into their trimethylsilyl derivatives for analysis of organic acids, methoxyphenols, cholesterol, sitosterol, and levoglucosan. The glass insert containing the sample was put into a 2 ml vial and sealed. The sample was then placed into a thermal plate (custom made) containing individual vial wells with the temperature maintained at 70°C for 2 hours. The calibration solutions were freshly prepared and derivatized just prior to the analysis of each sample set, and then all samples were analyzed by GC/MS within 18 hours to avoid degradation. The samples were analyzed by electron impact ionization GC/MS technique using a Varian CP-3400 gas chromatograph with a model CP-8400 Autosampler and interfaced to a Saturn 2000 Ion Trap Mass Spectrometer. Injections are 1 μl in size in the splitless mode onto a 30m long 5% phenylmethylsilicone fused silica capillary column (Factor Four VF-5MS) with an integrated 10m of deactivated guard column. Identification and quantification of the analytes are made by monitoring the base peak ions of each analyte and each deuterated analyte

FUELS AND FIRE PREPARATION

A variety of wildland fuels were used for a total of 75 burns. In addition, Kerosin was burned in in a lamp and a campfire (BlackDog) burn included a long lasting fire used to barbeque hot dogs. Fuels are listed and described in the following table including a fuel code that is used for data reporting. All fuels with the exception of Mt_Grass and Tundra_FM_Smolder were dry from long-term indoor storage.

Fuel Code	Fuel
Excelsior	A commercial poplar product used for insulation
Grass	Zambia (?) grass from Africa
Mt_Grass	Fresh wet grass harvested next to FSL
PP_Need	Ponderosa Pine Needles
PP_Wood	Ponderosa Pine Wood Sticks
Sage	Sagebrush
Tundra_FM_ Smolder	Feather Moss Tundra Cores from Alaska
WP_Need	White Pine Needles
BlackDog	Softwood campfire started with excelsior. BBQed hotdogs and Marshmellows
Ethanol	Ethanol is burnt as pool fire in a 8"(?) dish
Kerosene_Lamp	A commercial kerosene (storm) lamp, sooting strongly due to raised wick

Fuels were prepared for combustion on flat and sloping beds. Fuels on flat beds were arranged in a round "pie" shape and ignited in the center. Fuels on sloping beds were arranged in a rectangle and ignited either at the center bottom to yield a "heading" fire or at the top to yield a "backing" fire.

RESULTS

Results are summarized in the attached MS Excel spreadsheet containing 4 worksheets. Worksheet "Optical, Mass & OCEC" shows results from the measurements of optical absorption, scattering, and extinction, mass concentration from Teflon filters and the TEOM, and elemental (EC) and organic (OC) carbon concentrations. All measurements are at ambient conditions. Optical absorption has been measured with photoacoustic instruments at 532 nm and at 1047 nm, extinction by cavity-enhanced detection at 532 nm and scattering at 532 nm by the Integrating Sphere Integrating Nephelometer. Note that these data don't indicate closure, that is extinction = scattering + absorption. In some cases, the measurements are very close to closure, in other cases the sum of scattering and absorption coefficients is substantially larger than the measured extinction. We speculate that this is due to an inconsistent calibration of the DRI ISIN, however other possibilities include different size dependent particle sampling efficiencies for the three instruments and different temperature and relative humidity in the measurement volumes of the three instruments. Filter samples were generally accumulated over three burns with identical fuels, fuel preparation and ignition. TEOM measurements of real time PM mass concentration were normalized to the PM mass concentrations obtained from gravimetric analysis of the Teflon filters. The Teflon mass data are linked from the worksheet "Mass Data" that gives additional details. EC and OC concentrations are summarized and in the Worksheet "Optical, Mass & OCEC" and have been linked from the worksheet "Carbon Data". EC and OC concentrations have been determined following the IMPROVE protocol with the charring correction implemented by monitoring filter reflection (ECR and OCR) and or by monitoring filter transmission (ECT and OCT). The results of the organic filter analysis are contained in the worksheet "Organic Analysis Data" as function of fuels and burns with further details of the levoglucosan (the dominant organic fire marker) results shown in the worksheet "Levoglucosan Data".

PRESENTATIONS

Chen, L.-W. A., H. Moosmüller, W. P. Arnott, J. C. Chow, J. G. Watson, R. Susott, V. Kovalev, and W. M. Hao (2004). Variability of Physical and Optical Properties of Particles Emitted from Combustion of Wildland Fuels. *2004 Fall Meeting of the American Geophysical Union*, San Francisco, CA, December 13-17, 2004.

Moosmüller, H., W. P. Arnott, L. R. Rinehart, R. Susott, V. Kovalev, and W. M. Hao (2004). Characterization of Visibility Relevant Fire Emissions from Several Wildland Fuels. *Regional and Global Perspectives on Haze: Causes, Consequences, and Controversies (Visibility Specialty Conference)*, Asheville, NC, October 25-29, 2004.

Rinehart, L. R., D. E. Campbell, H. Moosmüller, J. C. Chow, and B. Zielinska (2004). Semi-Volatile Organic Compound Characterization of Biomass Combustion Emission for Prescribed Burns, Wildland Fuels, and Residential Wood Combustion. *Regional and Global Perspectives on Haze: Causes, Consequences, and Controversies (Visibility Specialty Conference)*, Asheville, NC, October 25-29, 2004.

PUBLICATION

Moosmüller, H., R. Varma, and W. P. Arnott (2005). Cavity Ring-Down and Cavity-Enhanced Detection Techniques for the Measurement of Aerosol Extinction. *Aerosol Sci. Tech.*, **39**, 30-39.

REFERENCES

Allen, G. (1998a). "Author's Response (Letters to the Editor)." *J. Air & Waste Manage. Assoc.* **48**, 197-199.

Allen, G., C. Sioutas, P. Koutrakis, R. Reiss, F. W. Lurmann, and P. T. Roberts (1997). "Evaluation of the TEOM® Method for Measurement of Ambient Particulate Mass in Urban Areas." *J. Air & Waste Manage. Assoc.* **47**, 682-689.

Allen, G. A. (1998b). "Invited Comment on: "Real-Time Liquid Water Mass Measurement for Airborne Particulates"." *Aerosol Sci. Tech.* **29**, 563-565.

Arnott, W. P., K. Hamasha, H. Moosmüller, P. J. Sheridan, and J. A. Ogren (2005). "Towards Aerosol Light-Absorption Measurements with a 7-Wavelength Aethalometer: Evaluation with a Photoacoustic Instrument and 3-Wavelength Nephelometer." *Aerosol Sci. Tech.* **39**, 17-29.

Arnott, W. P., H. Moosmüller, C. F. Rogers, T. Jin, and R. Bruch (1999). "Photoacoustic Spectrometer for Measuring Light Absorption by Aerosol: Instrument Description." *Atmos. Environ.* **33**, 2845-2852.

Arnott, W. P., H. Moosmüller, P. J. Sheridan, J. A. Ogren, R. Raspet, W. V. Slaton, J. L. Hand, S. M. Kreidenweis, and J. J. L. Collett (2003). "Photoacoustic and Filter-Based Ambient Aerosol Light Absorption Measurements: Instrument Comparison and the Role of Relative Humidity." *J. Geophys. Res.* **108**, 4034-4044, doi: 10.1029/2002JD002165.

Arnott, W. P., H. Moosmüller, and J. W. Walker (2000). "Nitrogen Dioxide and Kerosene-Flame Soot Calibration of Photoacoustic Instruments for Measurement of Light Absorption by Aerosols." *Rev. Sci. Instrum.* **71**, 4545-4552.

Chen, L.-W. A., J. Chow, J. G. Watson, H. Moosmüller, and W. P. Arnott (2004). "Modeling Reflectance and Transmittance of Quartz-Fiber Filter Samples Containing Elemental Carbon Particles: Implications for Thermal/Optical Analysis." *J. Aerosol Sci.* **35**, 765-780.

Chow, J. C., J. G. Watson, L.-W. A. Chen, W. P. Arnott, H. Moosmuller, and K. Fung (2004). "Equivalence of Elemental Carbon by Thermal/Optical Reflectance and Transmittance with Different Temperature Protocols." *Environ. Sci. Technol.* **38**, 4414-4422.

Chow, J. C., J. G. Watson, D. Crow, D. H. Lowenthal, and T. Merrifield (2001). "Comparison of IMPROVE and NIOSH Carbon Measurements." *Aerosol Sci. Tech.* **34**, 23-34.

Chow, J. C., J. G. Watson, L. C. Pritchett, W. R. Pierson, C. A. Frazier, and R. G. Purcell (1993). "The DRI Thermal/Optical Reflectance Carbon Analysis System: Description, Evaluation and Applications in U.S. Air Quality Studies." *Atmos. Environ.* **27A**, 1185-1201.

Christian, T. J., B. Kleiss, R. J. Yokelson, R. Holzinger, P. J. Crutzen, W. M. Hao, B. H. Saharjo, and D. E. Ward (2003). "Comprehensive Laboratory Measurements of Biomass-Burning Emissions: 1 Emissions from Indonesian, African, and Other Fuels." *J. Geophys. Res.* **108**, DOI:10.1029/2003JD003704.

Horodecki, J. and H. Fißan (1996). "Vergleich unterschiedlicher Kalibriermethoden für den Sensor eines TEOM®-Meßgerätes." *Staub-Reinhalt. Luft* **56**, 5-10.

Huntzicker, J. J., R. L. Johnson, J. J. Shaw, and R. A. Cary (1982). "Analysis of Organic and Elemental Carbon in Ambient Aerosol by a Thermal-Optical Method." In Particulate Carbon:

Atmospheric Life Cycle, G. T. Wolff and R. L. Klimisch (Eds.), *Plenum Press* (New York), 79-88.

Moosmüller, H. and W. P. Arnott (2003). "Angular Truncation Errors in Integrating Nephelometry." *Rev. Sci. Instrum.* **74**, 3492-3501.

Moosmüller, H., W. P. Arnott, C. F. Rogers, J. L. Bowen, J. Gillies, W. R. Pierson, J. F. Collins, T. D. Durbin, and J. M. Norbeck (2001a). "Time Resolved Characterization of Diesel Particulate Emissions. 1. Instruments for Particle Mass Measurements." *Environ. Sci. Technol.* **35**, 781-787.

Moosmüller, H., W. P. Arnott, C. F. Rogers, J. L. Bowen, J. Gillies, W. R. Pierson, J. F. Collins, T. D. Durbin, and J. M. Norbeck (2001b). "Time Resolved Characterization of Diesel Particulate Emissions. 2. Instruments for Elemental and Organic Carbon Measurements." *Environ. Sci. Technol.* **35**, 1935-1942.

Moosmüller, H., W. P. Arnott, C. F. Rogers, J. C. Chow, C. A. Frazier, L. E. Sherman, and D. L. Dietrich (1998). "Photoacoustic and Filter Measurements Related to Aerosol Light Absorption during the Northern Front Range Air Quality Study (Colorado 1996/1997)." *J. Geophys. Res.* **103**, 28149-28157.

Moosmüller, H., R. Varma, and W. P. Arnott (2005a). "Cavity Ring-Down and Cavity-Enhanced Detection Techniques for the Measurement of Aerosol Extinction." *Aerosol Sci. Tech.* **39**, 30-39.

Moosmüller, H., R. Varma, W. P. Arnott, H. Kuhns, V. Etyemezian, and J. A. Gillies (2005b). "Scattering Cross Section Emission Factors for Visibility and Radiative Transfer Applications: Military Vehicles Traveling on Unpaved Roads." *J. Air & Waste Manage. Assoc.*, submitted.

Okrent, D. A. (1998). "Optimization of a Third Generation TEOM® Monitor for Measuring Diesel Particulate in Real-Time." *SAE Tech. Pap. Ser.* **No. 980409**.

Patashnick, H. (1987). "On-Line, Real-Time Instrumentation for Diesel Particulate Monitoring." *Diesel Prog. N. Amer.* **41**, 1079-1083.

Patashnick, H. (1998a). "Letters to the Editor." *J. Air & Waste Manage. Assoc.* **48**, 195-197.

Patashnick, H. (1998b). "Rebuttal (Letters to the Editor)." *J. Air & Waste Manage. Assoc.* **48**, 199-200.

Patashnick, H. and C. L. Hemenway (1969). "Oscillating Fiber Microbalance." *Rev. Sci. Instrum.* **40**, 1008-1011.

Patashnick, H. and E. G. Rupprecht (1991). "Continuous PM-10 Measurements Using the Tapered Element Oscillating Microbalance." *J. Air & Waste Manage. Assoc.* **41**, 1079-1083.

Raspet, R., W., V. Slaton, W. P. Arnott, and H. Moosmüller (2003). "Evaporation – Condensation Effects on Resonant Photoacoustics of Volatile Aerosols." *J. Atmos. Ocean. Technol.* **20**, 685-695.

Rogers, C. F., J. G. Watson, D. Day, and R. G. Oraltay (1998). "Real-Time Liquid Water Mass Measurement for Airborne Particulates." *Aerosol Sci. Tech.* **29**, 557-562.

Shore, P. R. and R. D. Cuthbertson (1985). "Application of a Tapered Element Oscillating Microbalance to Continuous Diesel Particulate Measurement." Society of Automotive Engineers. Technical Paper, **850405**.

Varma, R., H. Moosmüller, and W. P. Arnott (2003). "Toward an Ideal Integrating Nephelometer." *Opt. Lett.* **28**, 1007-1009.

Whitby, R., R. Johnson, and R. Gibbs (1985). "Second Generation TEOM Filters - Diesel Particulate Mass Comparisons Between TEOM and Conventional Filtration Techniques." Society of Automotive Engineers. Technical Paper, **850403**.

Run Number	Sampling Date	Start Time	End Time	Comments	Mean 532 nm Absorption (1/Mm)	Mean 1047 nm Absorption (1/Mm)
11-13-03 PPNEED BURN 1	13-Nov-03	16:25:30	16:31:12	Ponderosa Pine Needles	1525.7	798.7
11-13-03 PPNEED BURN 2	13-Nov-03	17:39:51	17:48:41	Ponderosa Pine Needles	1259.7	692.3
11-13-03 PPNEED BURN 3	13-Nov-03	18:21:15	18:30:03	Ponderosa Pine Needles	1260.1	670.2
BURN 1+2+3					1266.3	684.1
11-14-03 EXCEL BURN 4	14-Nov-03	10:00:56	10:10:49	Excelsior	1296.9	695.1
11-14-03 EXCEL BURN 5	14-Nov-03	10:30:39	10:35:25	Excelsior	2941.9	1513.3
11-14-03 EXCEL BURN 6	14-Nov-03	11:06:20	11:13:18	Excelsior	1998.6	1030.3
BURN 4+5+6					1885.8	983.5
11-14-03 WPNEED BURN 7	14-Nov-03	11:54:53	12:04:40	White Pine Needles	677.2	349.1
11-14-03 WPNEED BURN 8	14-Nov-03	12:18:47	12:28:34	White Pine Needles	488.2	245.8
11-14-03 WPNEED BURN 9	14-Nov-03	14:24:10	14:32:53	White Pine Needles	638.2	322.8
BURN 7+8+9					599.8	305.3
11-14-03 GRASS BURN 10	14-Nov-03	14:59:55	15:09:39	Grass	180.4	81.8
11-14-03 GRASS BURN 11	14-Nov-03	15:24:56	15:34:32	Grass	218.2	98.3
11-14-03 GRASS BURN 12	14-Nov-03	15:50:20	16:00:09	Grass	306.8	146.5
BURN 10+11+12					235.4	109.0
11-14-03 PPWOOD BURN 13	14-Nov-03	16:34:02	16:43:41	Ponderosa Pine Wood	1972.4	1080.5
11-14-03 PPWOOD BURN 14	14-Nov-03	16:54:19	17:04:03	Ponderosa Pine Wood	1787.3	967.4
11-14-03 PPWOOD BURN 15	14-Nov-03	17:15:05	17:24:54	Ponderosa Pine Wood	1754.7	975.1
BURN 13+14+15					1837.5	1007.4

11-15-03 KEROSENE BURN	15-Nov-03	10:33:40	11:33:40	Kerosene	331.2	179.8
BURN 16					331.2	179.8
11-15-03 SAGE BURN 17	15-Nov-03	11:54:32	12:04:17	Sage	1384.9	647.6
11-15-03 SAGE BURN 18	15-Nov-03	12:36:33	12:46:17	Sage	1242.1	599.8
11-15-03 SAGE BURN 19	15-Nov-03	12:59:55	13:09:38	Sage	1202.0	557.3
BURN 17+18+19					1276.4	601.6
11-15-03 SAGE BURN 21	15-Nov-03	14:34:55	14:44:40	Sage	1619.1	822.9
11-15-03 SAGE BURN 22	15-Nov-03	14:59:57	15:09:47	Sage	1626.8	796.5
11-15-03 SAGE BURN 23	15-Nov-03	15:21:47	15:31:46	Sage	1393.1	694.3
BURN 21+22+23					1545.4	770.7
11-15-03 PPNEED BURN 24	15-Nov-03	15:50:29	16:00:14	Sage	1295.8	672.9
11-15-03 PPNEED BURN 25	15-Nov-03	16:10:45	16:20:36	Sage	1376.5	736.8
11-15-03 PPNEED BURN 26	15-Nov-03	16:31:07	16:42:33	Sage	1327.0	688.2
11-15-03 PPNEED BURN 27	15-Nov-03	16:53:03	17:02:44	Sage	1357.0	710.3
BURN 24+25+26+27					1338.6	701.5
11-15-03 WPNEED BURN 28	15-Nov-03	17:15:31	17:25:13	White Pine Needles	578.8	282.8
11-15-03 WPNEED BURN 29	15-Nov-03	17:36:55	17:46:33	White Pine Needles	754.8	389.4
11-15-03 WPNEED BURN 30	15-Nov-03	17:53:54	18:03:36	White Pine Needles	527.2	266.1
BURN 28+29+30					619.9	312.6
11-16-03 PPWOOD BURN 31	16-Nov-03	10:41:00	10:50:32	Ponderosa Pine Wood	1455.0	780.1
11-16-03 PPWOOD BURN 32	16-Nov-03	10:59:37	11:09:17	Ponderosa Pine Wood	1923.4	1041.5
11-16-03 PPWOOD BURN 33	16-Nov-03	11:21:24	11:31:05	Ponderosa Pine Wood	1937.9	1070.3

11-16-03 PPWOOD BURN 34	16-Nov-03	11:52:20	12:02:10	Ponderosa Pine Wood	1684.6	924.8
BURN 31+32+33+34					1751.0	954.7
11-16-03 GRASS BURN 35	16-Nov-03	12:19:35	12:29:36	GRASS	326.9	162.5
11-16-03 GRASS BURN 36	16-Nov-03	12:41:03	12:50:47	GRASS	323.8	159.4
11-16-03 GRASS BURN 37	16-Nov-03	13:00:11	13:10:04	GRASS	315.6	155.8
BURN 35+36+37					322.1	159.2
11-16-03 EXCEL BURN 38	16-Nov-03	13:33:55	13:40:52	Excelsior	1868.7	973.9
11-16-03 EXCEL BURN 39	16-Nov-03	13:49:52	13:56:51	Excelsior	1602.2	811.3
11-16-03 EXCEL BURN 40	16-Nov-03	14:27:42	14:34:42	Excelsior	1570.1	783.1
BURN 38+39+40					1679.9	855.8
11-19-03 WPNEED BURN 46	19-Nov-03	11:29:50	11:43:39	White Pine Needles backing	247.1	N/A
11-19-03 WPNEED BURN 47	19-Nov-03	12:01:19	12:10:43	White Pine Needles backing	457.7	N/A
11-19-03 WPNEED BURN 48	19-Nov-03	12:28:33	12:37:58	White Pine Needles backing	362.3	N/A
BURN 46+47+48					341.0	N/A
11-19-03 WPNEED BURN 49	19-Nov-03	14:44:57	14:54:47	White Pine Needles heading	125.7	N/A
11-19-03 WPNEED BURN 50	19-Nov-03	15:21:04	15:34:54	White Pine Needles heading	104.9	N/A
11-19-03 WPNEED BURN 51	19-Nov-03	15:55:34	16:09:39	White Pine Needles heading	126.8	N/A
BURN 49+50+51					118.5	N/A
11-19-03 SAGE BURN 52	19-Nov-03	16:57:32	17:11:21	Sage heading	707.6	N/A
11-19-03 SAGE BURN 53	19-Nov-03	17:24:31	17:33:57	Sage heading	1024.5	N/A
11-19-03 SAGE BURN 54	19-Nov-03	17:52:54	18:02:26	Sage heading	1146.1	N/A
BURN 52+53+54					926.3	N/A

11-20-03 SAGE BURN 55	20-Nov-03	10:41:41	10:54:48	Sage backing	1272.9	N/A
11-20-03 SAGE BURN 56	20-Nov-03	11:10:28	11:24:02	Sage backing	1410.1	N/A
11-20-03 SAGE BURN 57	20-Nov-03	11:36:47	11:50:29	Sage backing	1232.5	N/A
11-20-03 SAGE BURN 58	20-Nov-03	12:18:34	12:32:14	Sage backing	1130.1	N/A
BURN 55+56+57+58					1261.0	N/A
11-20-03 GRASS BURN 59	20-Nov-03	14:11:44	14:25:22	Grass heading	141.5	N/A
11-20-03 GRASS BURN 60	20-Nov-03	14:43:14	14:52:38	Grass heading	318.6	N/A
11-20-03 GRASS BURN 61	20-Nov-03	15:11:10	15:20:38	Grass heading	347.6	N/A
BURN 59+60+61					252.8	N/A
11-20-03 GRASS BURN 62	20-Nov-03	16:08:50	16:22:41	Grass backing	124.7	N/A
11-20-03 GRASS BURN 63	20-Nov-03	16:34:17	16:43:49	Grass backing	191.5	N/A
11-20-03 GRASS BURN 64	20-Nov-03	16:56:45	17:06:19	Grass backing	206.0	N/A
BURN 62+63+64					167.6	N/A
11-21-03 PPNEED BURN 65	21-Nov-03	10:05:06	10:18:59	Ponderosa Pine Needles hea	542.3	N/A
11-21-03 PPNEED BURN 66	21-Nov-03	10:32:20	10:41:54	Ponderosa Pine Needles hea	785.0	N/A
11-21-03 PPNEED BURN 67	21-Nov-03	11:08:51	11:18:21	Ponderosa Pine Needles hea	859.0	N/A
11-21-03 PPNEED BURN 68	21-Nov-03	11:33:37	11:43:05	Ponderosa Pine Needles hea	681.7	N/A
BURN 65+66+67+68					699.1	N/A
11-21-03 PPNEED BURN 69	21-Nov-03	12:13:14	12:27:08	Ponderosa Pine Needles bacl	811.5	N/A
11-21-03 PPNEED BURN 70	21-Nov-03	12:45:27	12:54:55	Ponderosa Pine Needles bacl	1039.8	N/A
11-21-03 PPNEED BURN 71	21-Nov-03	13:07:40	13:17:12	Ponderosa Pine Needles bacl	965.8	N/A
BURN 69+70+71					921.9	N/A
11-21-03 CAMPFIRE BURN 7	21-Nov-03	13:35:00	14:44:00	Campfire cooking	714.6	N/A

BURN 72					714.6	N/A
11-21-03 TUNDRA BURN 73	21-Nov-03	15:44:58	17:00:00	Tundra feather moss	13.4	N/A
BURN 73					13.4	N/A
11-21-03 MT GRASS BURN 7	21-Nov-03	17:55:55	18:09:52	Grass Montana heading	30.4	N/A
BURN 74					30.4	N/A
11-21-03 MT GRASS BURN 7	21-Nov-03	18:27:58	18:41:56	Grass Montana backing	36.9	N/A
BURN 75					36.9	N/A

Mean 532 nm Scattering (1/Mm)*	Mean 532 nm CED Extinction (1/Mm)	Teflon Filter Mass Conc. (ug/m3)"	Normalized TEOM Mass Conc. (ug/m3)"	ECR (ug/m3)	ECT (ug/m3)	OCR (ug/m3)	OCT (ug/m3)
1908.4	3305.4		N/A				
978.5	1793.6		N/A				
820.8	1663.4		N/A				
924.2	1766.7	290.1	N/A	174.0	161.7	111.3	123.5
1082.8	1780.0		368.2				
4468.7	5286.7		949.5				
1377.9	2537.6		447.9				
1924.5	2797.4	522.3	522.1	283.8	255.3	173.8	202.3
3326.4	3015.1		611.9				
4654.9	3972.0		943.1				
4552.8	3968.0		908.1				
4163.9	3639.8	819.8	817.8	185.1	133.1	379.7	431.7
1919.9	1688.2		309.9				
1183.5	1165.5		234.7				
722.2	919.7		224.1				
1274.0	1257.3	255.9	256.2	68.7	49.7	169.0	188.1
877.4	2466.4		443.3				
784.1	2220.9		236.4				
776.5	2177.3		199.4				
812.4	2287.4	287.2	292.3	239.6	233.1	50.2	56.8

150.5	546.0		50.2				
150.5	546.0	50.4	50.2	46.1	45.6	28.7	29.3
1992.8	2526.3		607.9				
960.7	1738.4		456.5				
1086.1	1775.2		447.1				
1347.0	2013.7	505.4	503.9	156.8	145.1	158.0	169.6
1185.2	2159.5		534.9				
983.9	2064.2		507.8				
1335.2	2122.6		539.7				
1168.9	2115.3	527.8	527.5	201.2	183.2	119.8	137.8
1210.4	2067.3		312.6				
747.1	1782.4		269.5				
999.8	1931.5		315.3				
1280.8	2119.8		358.2				
1055.9	1972.7	313.9	313.8	247.7	208.1	138.8	178.4
3891.5	3421.6		N/A				
3699.1	3379.5		N/A				
3899.2	3349.3		N/A				
3830.2	3383.5	726.4	N/A	147.2	108.1	354.0	393.0
676.6	1893.4		275.8				
787.1	2350.1		300.7				
759.3	2371.4		309.3				

705.0	2126.2		292.6				
732.1	2186.1	293.7	294.7	233.3	226.7	30.3	36.9
242.2	575.8		N/A				
331.2	621.7		N/A				
242.9	534.4		N/A				
271.7	577.1	107.5	N/A	48.1	45.2	64.5	67.4
1270.2	2305.4		427.9				
1997.8	2771.1		505.0				
1320.8	2219.0		415.0				
1529.8	2431.9	448.8	449.3	222.1	207.9	106.7	120.9
1294.4	1099.6		N/A				
1202.0	1230.4		N/A				
2592.8	2012.3		N/A				
1642.5	1400.6	416.6	N/A	78.2	57.7	203.8	224.3
4563.3	3168.1		N/A				
4959.2	3288.2		N/A				
6351.6	4151.1		N/A				
5375.6	3578.9	1281.0	N/A	47.7	33.4	752.0	766.3
1440.4	1521.2		N/A				
1092.0	1608.1		N/A				
1533.0	1940.3		N/A				
1367.1	1668.1	448.9	N/A	124.5	109.6	151.9	166.8

1059.4	1863.8		N/A				
1009.9	1887.0		N/A				
1132.6	1830.3		N/A				
817.8	1529.4		N/A				
1004.4	1776.6	433.4	N/A	155.2	150.1	88.5	93.5
115.7	265.5		N/A				
156.9	464.8		N/A				
216.8	547.6		N/A				
157.1	405.3	75.7	N/A	36.6	33.9	37.7	40.3
134.3	276.9		N/A				
221.8	429.8		N/A				
261.0	469.0		N/A				
196.4	376.9	85.7	N/A	26.0	23.5	46.1	48.6
1539.6	1584.7		N/A				
1867.9	2058.0		N/A				
2960.9	2524.9		N/A				
2386.2	2338.1		N/A				
2120.9	2070.1	468.7	N/A	123.3	100.9	247.1	269.5
514.2	1174.3		N/A				
627.0	1511.9		N/A				
520.7	1360.3		N/A				
548.6	1325.4	216.9	N/A	132.5	122.9	69.6	79.2
1651.9	1951.0		N/A				

1651.9	1951.0	531.8	N/A	141.1	94.2	248.2	295.1
1951.8	1397.1		N/A				
1951.8	1397.1	220.3	N/A	6.5	2.3	217.5	221.6
1215.9	1014.4		285.8				
1215.9	1014.4	286.2	285.8	11.4	5.7	246.8	252.4
2432.4	1797.4		481.5				
2432.4	1797.4	482.1	481.5	28.7	4.7	302.1	326.1